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Two-dimensional photonic crystal fabrication using fullerene films

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Abstract. The two-dimensional rectangular network has been fabricated firstly on the base of fullerene films using electron lithography. Such system shows the optical properties of the two-dimensional photonic crystal. The formed periodical structure may be transmitted easy into the semiconductor substrate by plasma etching due to the resistive properties of solid state fullerenes.

The aim of the work was the development of new electron lithography method of photon crystal structures fabrication by using fullerene films. Fullerenes are a perspective material for this purpose due to the possibility of their easy structure modification and therefore simple technological treatment. Moreover this particularity is typical for a lot of fullerene based composite materials possessing setting optical properties.

Initial objects to fabricate investigating structures are the films from fullerene C_{60} . Fullerene films were deposited on GaAs (100) substrates by vacuum thermal sublimation of 99.9% pure C_{60} -powder from a Knudsen-cell at 350°C . During the deposition at a rate of 0.2 nm/s the substrates were held at room temperature under residual pressure 10^{-5} Torr . The thickness of the films was varied from 300 to 500 nm.

For modeling the photonic crystal geometry we fabricated the regular C_{60} structures in the shape of rectangular network with the period 300–600 nm (see Fig. 1(b) with the best lattice). The total network area with uniform parameters exceeded 1 mm^2 that was suitable for the optical measurements. An electron lithography technique was employed to prepare the nanostructures using scanning electron microscope CamScan Series 4-88 DV 100 with the acceleration voltage $U = 10\text{--}40\text{ kV}$ and beam current $I = 10^{-10}\text{--}10^{-8}\text{ A}$. The external scan control was realized with industrial two-channel 14 bit digital-analog converter card. The scan step was less than 50 nm. The time of single dot exposure did not exceed 5 ms that corresponded to the reasonable exposure time for the entire sample. In the case of C_{60} -films the main contribution to the polymerization process was made by primary electrons of the beam and also by the back-scattered electrons (BSE) from GaAs substrate. A proximity effect led to the depending of the irradiation dose on structure geometry, and scan step. To take into account the contribution to the total irradiation dose from neighboring dots the BSE generation function for GaAs [1] was used. It was shown that in the case of lined structure one should use almost twice shorter exposure than for the array of dots. To get the proper shape for the crossed lines exposure time should be varied with distance to the crossing point according the generation function. The strong structure performance dependence on beam energy density was observed. At accelerating voltage higher than 30 kV one should use the beam current higher than 5 nA because the most part of beam energy dissipated into the substrate. So high density of the beam energy in the incident point led to C_{60} destruction and formation carbon clusters which lateral dimension is close to the period of the structure (see Fig. 1(a) with the worst lattice). The part of beam energy

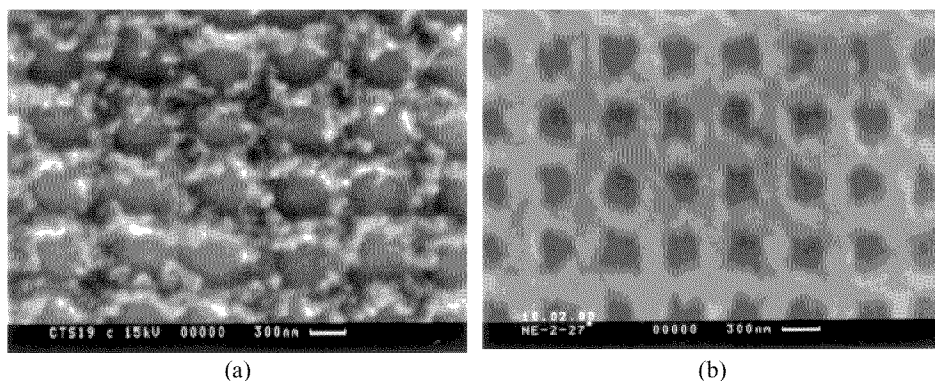


Fig. 1. Fullerene based networks made on GaAs substrate at two different regimes of electron exposure: (a) $U = 30$ kV, $I = 6$ nA; (b) $U = 15$ kV, $I = 1$ nA.

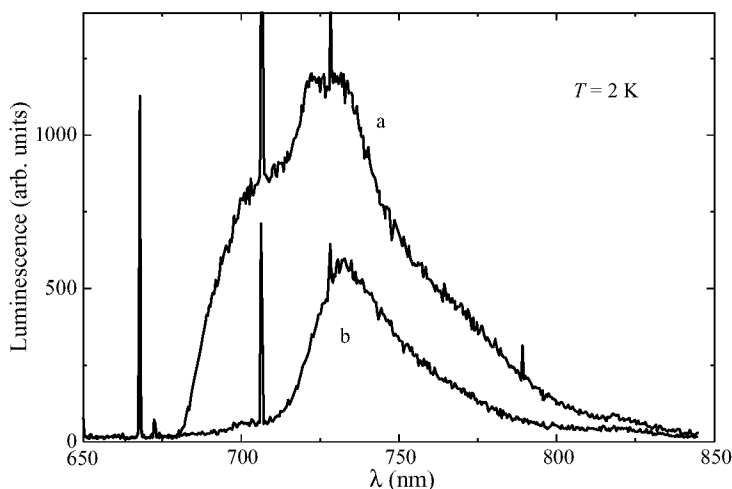


Fig. 2. The luminescence spectrum of C_{60} films at $T = 2$ K: (a) initial, (b) after electron beam exposure. Excitation wavelength is 441.6 nm.

dissipated in the fullerene film rose with accelerating voltage decreasing. The lithography performance was improved by using $U = 15$ – 20 kV.

The process of fullerene film electron modification was investigated and controlled with help of spectroscopic measurements. The studies of photoluminescence C_{60} film have shown the luminescence line shape modification depending on the character of interaction between electron excitation in solid state fullerene and their phonon system and also depending on features of exciton–polaron recombination [2] (see Fig. 2). Moreover it has observed the significant decreasing of luminescence intensity of fullerene film after electron exposure. This fact is due to arising number of polymerizing fullerene molecule complexes playing a part of non-radiate recombination centers in fullerene film.

The polymerized parts of film are characterized by very low solubility as compared with initial film. The exposed films were developed with toluene during 5–60 s. The developing procedure followed immediately after the exposure to avoid depolymerization effect as well as to prevent sample from environmental impact. If the irradiation dose was

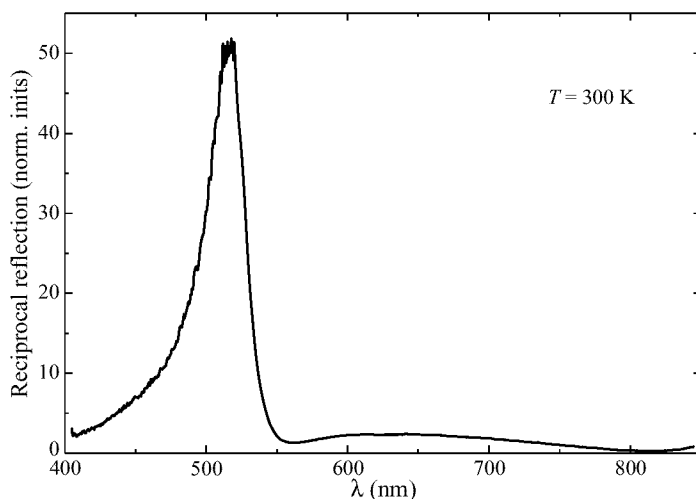


Fig. 3. Reciprocal reflection spectrum of fullerene based network on GaAs substrate normalized by reflection of film initial for fabrication of network.

enough for complete polymerization, irradiated part of the film remains on the substrate after developing while the regions with pristine fullerene were completely dissolved in toluene.

The regular structures with line height up to 500 nm fabricated by this means possess optical properties of two-dimensional photonic crystal that have been verified by reflection studies. It is significant for opto-electronic applications that the reflectivity of structures may be changed by many times with help of similar regular coating. This fact is demonstrated in Fig. 3.

The formed regular fullerene based structure may be easily transmitted into semiconductor substrate by ion etching due to high aspect ratio of polymerized fullerenes as a resist for plasma etching. The ion beam etching process was carried out in a specialized Rocappa machine. This is a standard ion beam milling system with 5 cm filamentless ion beam source (Anatech Ltd). The chamber at the milling machine pumped down to low vacuum by oil free Drytec system and turbomolecular pump (less than 2×10^{-7} mbar). The flexible mechanical design of the gun holder allows us to tilt the substrate with respect to the beam axis. Total gas pressure (Ar) in the gun is adjusted to $(3.0-4.0) \times 10^{-4}$ mbar, and the ion beam acceleration voltage 300 V, current density 0.5 mA/cm^2 and sample temperature 25°C .

With help of described method the GaAs substrate was etched through regular fullerene based mask on depth up to 400 nm. This simple method allows us to fabricate the semiconductor photon type structure with required geometry. The example of structure obtained in such a way is shown in Fig. 4.

Thus, the great potential possibility to fabricate the photonic structures using fullerene films is demonstrated in this work.

Acknowledgements

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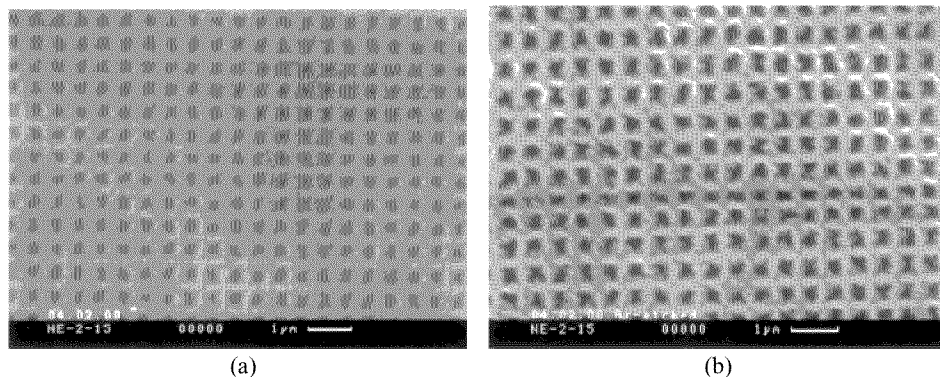


Fig. 4. The images of submicron regular network based on: (a) fullerenes, (b) made by ion etching of GaAs substrate through fullerene mask.

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